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FINAL TECHNICAL REPORT

to

Air Force Office of Scientific Research
on project entitled

"NEW MATERIALS FOR SPACECRAFT STABILITY AND DAMPING
A FEASIBILITY STUDY"

Contract No. AFOSR-83-0221

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ABSTRACT

A preliminary feasibility study has been conducted on some new materials for use as structure components of spacecrafts. These included some new glasses, glass-ceramics, fibers and composites such as low expansion copper aluminosilicate glasses, hollow and oval glass fibers and hollow fiber-glass-polymer composites. The low temperature expansion coefficients, elastic moduli and damping constants were measured. Recommendations are made for further research and development of some selected materials which appeared to be promising candidates for spacecraft structures.

I. INTRODUCTION

Although the many components of a large precision space structure perform difference function, most of them must be designed to withstand the "hostile" environment of outer space. Some obvious conditions under which long-term satisfactory performance are expected are high vacuum, external radiations and cyclic temperature variations from -200°C to +200°C. Secondly, the total weight of the structure should be as low as possible. Thirdly, for sensitive instrumentations, vibrational perturbations are undesirable and hence must be minimized or completely damped out.[1,2] Because of structural connectivity and the difficulty of isolation, the variation in certain properties of each component should also be minimized. The need for minimal changes in the shape or dimensions under induced forces and temperature variations is an example. Thus for an ideal spacecraft possessing long-life, great stability and maximum damping, the selection of proper engineering materials is of equal importance to mechanical design.

In general, engineering materials having low coefficients of thermal expansion, low density and high elastic modulus are of obvious importance.[1,2] In addition, they should be resistant to radiation and exhibit low or no outgassing.[1,2] For some components, the materials should be capable of damping out pertubations over the frequency range from 0.1 to 10,000 Hz. For other components the possibility of electrical charging is an important consideration and hence the surface or bulk electrical conductivity must be considered.[2] Frequently, a single-phase materials is unable to meet the stringent requirements of space applications and composites must be used.[1]

Recently, many new engineering materials (including composites) have been studied and a number of new material preparation processes have also been developed. Good examples of these are new high modulus fiber-inorganic glass and glass-ceramic matrix composites developed by K. M. Prewo and co-workers.[3-6] For graphite fibers-borosilicate glass matrix composites, For example, the average expansion coefficients are very low from 25° to 150°C, the density is approximately 2 gm/cc and the elastic modulus is over 200 GPa (over 30×10^6 psi). for SiC fibers-glass ceramic composites, the average expansion coefficients are approximately 2×10^{-6}/deg. from 20°C to 100°C, the romme temperature elastic moduli are about 140 GPa (20×10^6 psi) and the density around 2 gm/cc. Although data on some properties are still lacking, especially at very low temperatures, such new composites will obviously be of interest to designers of precision space structures.

The type of new composites developed by Prewo and co-workers is not the only new and promising materials available. In the last few years, a variety of other new monolithic materials (glass and glass ceramics) and composites has been reported which appear to be promising. The main objective of this project is to examine the feasibility of these relatively new materials on a preliminary basis for use in precision space structures. This is the final technical report of this one-year preliminary feasibility study. In the following section, the background on some of these materials will be presented. The other sections are summaries of the research performed by the UCLA team in the one-year period ending September 30, 1984. This is comprised of literature survey and some experimental research.

II. SOME NEW MATERIALS, NEW MATERIAL PROCESSES AND NEW CONCEPTS

The word "new" is naturally relative. For this project it is meant to imply that applications to precision space structures have not been carefully evaluated. In the selection of such new materials, the criteria are high probability for achieving one or more of the following: low thermal expansion, high stiffness, low density, controllable porosity and pore geometry, controllable electrical properties, minimum outgassing in vacuo, controllable damping and low thermal conductivity.

A. Some New Glasses and Glass-Ceramics

(a) Glasses based on copper aluminosilicates[7-10]

Glasses in the system $Cu_2O-Al_2O_3-SiO_2$ have low thermal expansion coefficients from 0° to 300°C. Expansion coefficients similar to that of fused silica (0.5 to 10^{-6} per deg) have been reported. The densities are in the range of 2.7 to 2.9 gm/cc. Melting can be made at 1550°C, considerably less than that for silica or TiO_2-SiO_2 glasses. With minor additions of various fluxes such as B_2O_3, melting can be done at 1450°C without serious effects on the expansion coefficients. Although , elastic modulus values are available, the hardness of these glasses are typically some 40-50% higher than those for silica glass and 100% higher than that of Corning 7740 (a low expansion borosilicate glass with an expansion coefficient of 3.2×10^{-6} per deg.). It is anticipated that the $Cu_2O-Al_2O_3-SiO_2$ glasses will have relatively higher elastic modulus. The softening temperatures can be as low as the 7740 glass.

It is thus anticipated that they can be used as a matrix materials for the containment of high modulus fibers with improved stiffness and less thermal distortion.

The $Cu_2o-Al_2O_3-SiO_2$ glass are practically black in color and their powder can be used as a glazing material. On treatment in a reducing atmosphere, the surface can be reduced to give a highly effective metallic coating. Thus electrical, optical and thermal properties of the surface can be controlled. Glass fibers have been made and will be of interest because of their low expansion, optical and electrical properties.

(b) Glass-Ceramics based on $Cu_2O-Al_2O_3-SiO_2$ Glasses[10-12]

The $Cu_2O-Al_2O_3-SiO_2$ glasses can be easily nucleated and crystallized to have glass-ceramics of low, zero or negative expansion coefficients. Their potential roles will be similar to those for the parent glasses. It is conceivable that glass-ceramic fibers can also be made.

(c) $Li_2O-Al_2O_3-SiO_2$ Glass-Ceramic Fibers

Glasses based on $Li_2O-Al_2O_3-SiO_2$ can be crystallized to give glass-ceramics of extremely low thermal expansion coefficients. Further the bulk glass-ceramics have been chemically strengthened through ion-exchange.[13] Theoretically, it is possible to increase the elastic modulus through ion-exchanged because of surface compression.[14] Recently, fibers based on $Li_2O-Al_2O_3-SiO_2$ were converted to glass-ceramic fibers.[15] The fibers have low or zero expansion coefficients, highs strengths and are transparent in the visible. Preliminary work at UCLA has confirmed that they can be ion-exchanged in a KNO_3 melt to increase both strength and elastic modulus.

(d) Impregnated porous glass

It is well known that certain glasses based on $Na_2O-B_2O_3-SiO_2$ are easily phase-separated and leached to give a so-called microporous glass. The pores are interconnected and pore diameters can be controlled in the range of 20 to 200 A. Recently, research at UCLA under AFOSR support has shown that the porous glass can be impregnated with many materials. When the pores are subsequently collapsed by heating, the impregnants can be transformed into isolated sub-micron particles dispersed in the SiO_2 matrix. Oxides such as ZrO_2 and TiO_2 have been impregnated this way to give a two-phase body. If one were to assume that a porous glass with 50% porosity is impregnated with Al_2O_3 and that after all the pores are collapsed, the SiO_2 matrix now contains some 40% by volume of Al_2O_3, then the expected elastic modulus is 27×10^6 psi. There is thus the possibility of a new solid with extremely low expansion but very high stiffness. Other oxides such as V_2O_5 and metals such as Ag have also been impregnated this way. The possibilities thus also exist for low expansion solids with unique optical properties. Dependent on the concentration of residual pores and the nature of the impregnate, the damping coefficient can also conceivably be controlled.

Inpregnated porous glass can be drawn into fibers readily with the simultaneous collapse of pores. It is evident that a low expansion high modulus fiber can be made this way.

B. New Ceramic Processing - the Sol-Gel Method

In recent years, the so-called sol-gel method has been receiving a great deal of scientific and technical interest.(16) Briefly, organo-metallic compounds are dissolved in alcoholic solutions, hydrolyzed and polymerized to form gels. The excess water and unreacted organics are then removed by vacuum and/or thermal treatment. The gels are porous and on heating to temperatures below the glass transition, most, if not all of the pores are eliminated. The dense glasses from the gels apparently have identical properties to the melt-formed glasses.(16) Glass-ceramics can also be made this way. A method thus exists for using the sol-gel approach for the fabrication of composites with a glass or glass-ceramic matrix at much lower temperatures. For instance, in the fabrication of SiC fiber-borosilicate glass composites, a temperature of 1200°C is needed although T_g is only 600°C for the glass. The fabrication temperature will be in excess of 2000°C if silica glass is to be used as the matrix. Theoretically, a silica glass matrix can be fabricated at 700°-800°C via the sol-gel method. Although the sol-gel method suffers from the problems of organics and water removal plus large volumetric contractions, it must be considered as a potentially important technique for the preparation of composites.

In many sol-gel systems, after the water and organics have been almost entirely removed, the gels are still highly porous. The porous gels can be impregnated and fired porous gels offer potentials as materials with controllable damping coefficients and low thermal conductivities.

C. Exploitation of Fiber Geometry

(a) Hollow fiber

A hollow glass fiber can be easily made by the drawing of a thick-walled tube. Recently, in a research program supported by AFOSR at UCLA, hollow glass fibers having an i.d. of 10μ and an o.d. of 30μ have been fabricated. The ratio of i.d. to o.d. is easily controlled. It is known that hollow fibers can also be drawn directly from the melt with a special bushing. Fibers used in composites are invariably solid round fibers. For two composites to have equal stiffness, the weight of that using hollow fibers can be significantly less than that using solid fibers assuming the chemical compositions and hence densities of the two fibers are similar. As much as 30% decrease in weight is possible. Not only do hollow fibers offer weight advantages, but they can be used to lower thermal conductivity as well as controlling damping. Further they can act as sealed containers for organic polymers. The outgassing problem can thus be eliminated. The concept of hollow glass fibers containing organic polymers embedded in a glass or ceramic matrix, fabricated via a sol-gel method, offers the potential for a new family of solid composites with low expansion, high stiffness, high damping coefficients, inertness to radiation damage and no outgassing problems.

(b) Oval Fiber

Many glasses are easily fabricated into a variety of shapes because of their advantageous viscosity-temperature relationships. Ropund glass fibers and thin glass tapes are commercially available. There is no reason why an oval-shaped glass fiber cannot be drawn continuously through a specially shaped bushing. For two glass fibers with the same cross-sectional area, the stiffness of the oval-shaped fiber in the long direction can be significantly higher than that of the round fiber. Thus for a round fiber with a diameter of 10μ and an oval-shaped fiber whose long and short dimensions are 20μ and 5μ respectively, the cross-sectional areas are similar. However, the stiffness along the 20μ direction is FOUR TIMES larger than that of the 10μ round fiber. The alignment of the oval fiber in a matrix should not be difficult. Hence the stiffness of a composite can be greatly increased in certain directions. In a sense, then, the "effective" elastic modulus of a glass fiber can be 40×10^6 psi although its true modulus is only 10×10^6 psi.

D. Glass Microballoons

Glass microballoons known as "eccospheres" and "cenospheres" have been commercially available for a long time. The have been used as fillers for organic resins.(17) The external diameters can be varied from 20μ to 200μ. Both borosilicates and silica microballoons are available.(18) The density of individual balloons can be as low as 0.25 gm/cc versus the 2.5 to 3.0 gm/cc values for the bulk glass. Microballoons have been self-bonded or bonded with ceramic frits to give light-weight, heat-insulating and high-temperature stables bodies.(19) The optical properties can be controlled by the addition of inorganic oxides such as CoO to the frit.(19)

It would appear that it is entirely feasible to prepare low-density composites with controlled and graded porosity by the embedment of microballoons in a glass or glass-ceramic matrix. The sol-gel method for the fabrication of the matrix is particularly attractive because the composite can be fabricated at low temperatures. The expansion coefficients of the hollow microspheres can be matched to that of the matrix. Conceivably then, the use of silica microballoons and a silica glass matrix will result in a low expansion composite which can have low density as well as graded porosity. Silica microballoons can also be sintered with copper aluminosilicate glass frits to form low expansion bodies.

III. RESEARCH PERFORMED

A. Literature Search

A literature research was conducted through the UCLA Research Library. The primary objective was to conduct a broad survey regarding the types of materials used or considered for use in spacecraft structures. A list of 68 important references is furnished in Appendix 1. From this list, important technical information was extracted from nine of the reports. A summary is shown in Table 1. As seen in this table, graphite-epoxy composites appeared to be the most important type of materials used or contemplated. No published information was found on the types of materials discussed in Section II of this report. Because of this lack of information, some experimental research was conducted at UCLA.

B. Measurement of Expansion Coefficients

The expansion coefficients of a number of materials were determined from -200° to +100°C. An apparatus was designed and constructed for this purpose. This equipment is shown in Figure 1 and is based on expansion-induced pressure on a transducer. A list of the materials studied in this project and their

TABLE 1: Simplified literature summary of Materials considered for space structural applications.

AUTHOR	REF. NO.	MATERIALS(S)	APPLICATION	PROCESSING	JUSTIFICATION
Vaughn	23	Graphite/epoxy structural tubes	columns for space platform support.	Graphite fibers are held in proper geometry by dry fiber placement. Resin is pressure injected into tooling. Tooling is pressure-heated and resin is cured *in situ*	
Armstrong	25	Metal-matrix composite	satellite system structural elements.	Fibers of graphite, boron, silicon carbide or alumina are cast in a matrix of aluminum or magnesium adsorption	High stiffness, low expansion, high conductivity, low outgassing, low moisture
Hammond	35	Graphite/epoxy as substitute for Invar	Lightweight thermally stable components in communication satellites	standard	low thermal
Krumweide	41	Graphite/epoxy	reflectors	standard	low thermal distortion
Lager	42	Graphite/epoxy	Truss elements	standard	Low thermal distortion is required so truss can be used as netering structure (reference plane).
Mayer	43	Carbon fiber composites	Rocket engine motor casings, advanced systems, space shuttle components, telescope assemblies, energy generation systems, etc.	A wide variety of processing antenna tailor properties to application needs.	A wide variety of combinations of techniques to achieved.

TABLE 1: Simplified literature summary of Materials considered for space structural applications (continued).

AUTHOR	REF. NO.	MATERIALS(S)	APPLICATION	PROCESSING	JUSTIFICATION
MDAC	44	Composite geodatic beam composed of an equilateral grid-work of criss-crossing rods.	Large truss sections for platform support	Incorporate a new graphite and glass reinforced thermo-plastic resin with low thermal expansion thermal gradients.	Combination of materials and design achieves high stiffness with minimal structural distortion due to
Wade	68	Graphite reinforced metal-matrix composites	Deployable antennas.	Possible systems include graphite/aluminum and graphite/magnesium	Low structural distortion due to thermal gradients, dynamic response, high specific stiffness, high thermal conductivity, low thermal expansion, and low moisture adsorption
Gounder	10	Kevlar/epoxy graphite/epoxy glass epoxy	Satellite hardware reflectors, feed towers, multiplex microwave filters, precision mounting instrument plat-forms, solar panel substrates, and subsystem hardware.	Multilayer con-figurations for most effective use of unidirectional and woven materials.	Lightweight, high stiffness, high strength, RF trans-parency

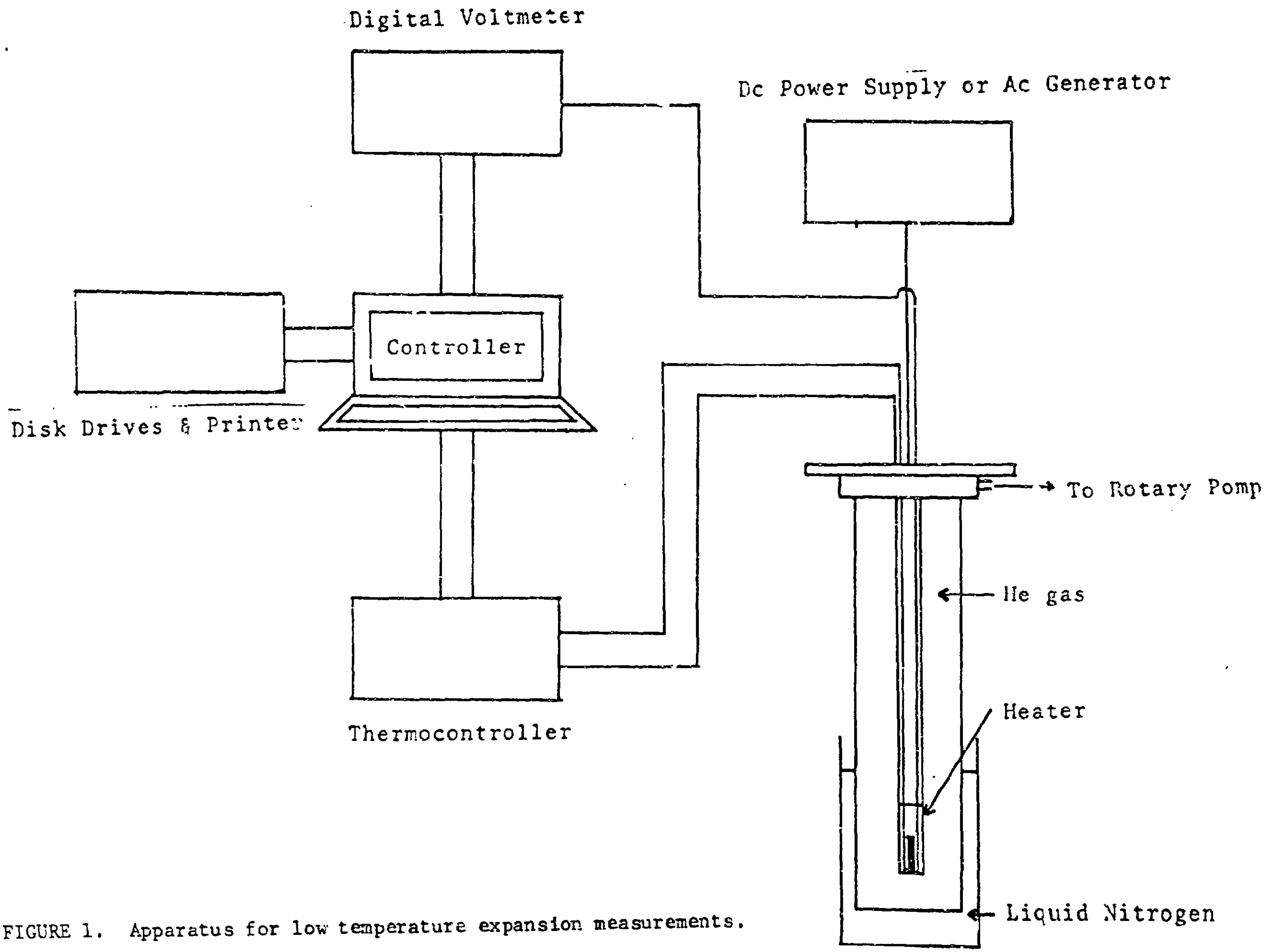

FIGURE 1. Apparatus for low temperature expansion measurements.

sources are listed in Table 2. The average expansion coefficients over the temperature range of -200°C to +100°C are shown in Table 3.

Some significant points to note are: (a) For the resin-glass sphere (microballoons) composites, because the resin is the matrix phase, it has a larger effect on the expansion despite the fact that the glass spheres may be the major component by volume. Thus the expansion of the resin is 624×10^{-7} as compared to the value of only 368×10^{-7} for a 70% glass sphere sample when the glass phase is a low expansion glass. The density of the resin is 1.134 g/cc as compared to that of the 70% glass sphere sample of 0.624 g/cc (see Table 3). The possibility thus exists for low density composites with relatively high expansion coefficients. (b) The copper aluminosilicate glass does have very low expansion coefficients even down to -200°C. (c) Silica gels, although fired only at 400°C and thus have very high porosity (in excess of 40%) already exhibits the low expansion (5×10^{-7}) of silica glass even down to low temperatures.

Results of samples of silica gels fired at different temperatures are shown in Figure 2 which includes results of apparent density, that is the density of the "skeleton" without the open pores. Results of resin-glass microballoon composites are shown in Figure 3.

C. Measurement of Elastic Moduli

The elastic moduli (Young's modulus, shear modulus and Bulk modulus) and the Poisson's ratio of a number of materials were determined from transverse and longitudinal velocities measurements and density measurements based on standard methods[20] using small rods as samples. In addition to the

TABLE 2: Information on materials studied in present project.

MATERIAL	SOURCE	COMMENTS
Alumina	Diamonite	99% dense.
Resin	Plastic Mart	Laminating Rosin (PM-15C)
PMMA	Alfa Ventron	Received as methylmethacrylate monomer. Catalyzed with benzoil peroxide, set at 45°C, and cured at 57°C
Microballoons	Emerson and Cuming, Inc.	see attached data sheet, Appendix 2
Hollow Fibers	UCLA	Drawn from soda-lime-silicate tubing. Ave, diameter 50 micron
Glass-Aluminum Fibers	UCLA	Co-drawn from 99% pure aluminum rod and soda-lim-silicate glass tubing. Ave, diameter 50 microns
Silica Glass	Hereaus Amersil	T08 Commercial
Pyrex Glass	Corning	7740
Li_2O-Al_2O_3-SiO_2 glass-ceramic	UCLA	Pyroceram 9608
CuO-Al_2O_3-SiO_2	UCLA	$12.5Cu_2O$-$12.5Al_2O_3$-$75SiO_2$ Made by melt-quenching
High purity alumina polycrystalline		
Silica Gel	UCLA	HF-catalyzed gel produced from TEOS, ethanol, and water. Porosity = 65%.
SiC-SiO_2 Composite	UCLA	HF-catalyzed gel matrix with 33w/0 SiC and 33w/o cab-o-sil
Cab-O-Sil	Cabot Corp.	Fumed amorphous silica powder with particle size = 200 nm.
SiC	Buehler	600 grit (9-12 micron), 96% purity

TABLE 3: Average thermal expansion from -200°C to +100°C except for results from literature.

MATERIAL	THERMAL
resin + hollow glass sphere	
(0% glass sphere)	624
(20% glass sphere)	561
(50% glass sphere)	430
(60% glass sphere)	412
(70% glass sphere)	368
SiO_2 melted and quenched glass	5
$CuO-Al_2O_3-SiO_2$ melted and quenched glass	5
Al_2O_3	88*
ZrO_2 (stabilized)	100*
MgO	
SiC	47*
B_4C	45*
TiC	74*
Mo	Si_2
Si_3N_4	23-36*
SiO_2 gels	
(fired at 400°C)	5
(fired at 600°C)	5
(fired at 800°C)	
SiO_2 + SiC composite	
(fired at 600°C)	37
(fired at 1000°C)	12
-	
Porous glass + PMMA	138

*from literature

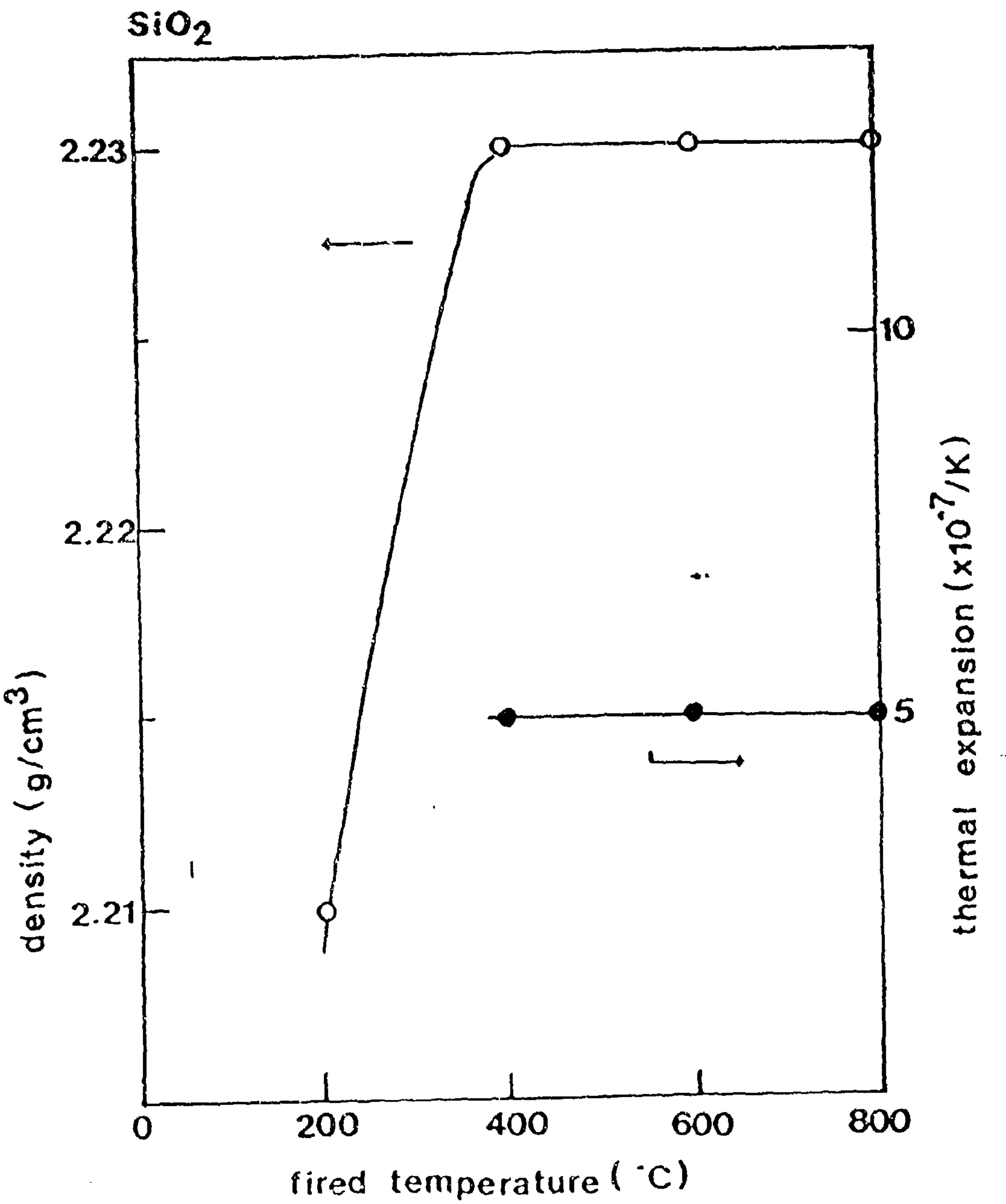

FIGURE 2: Expansion and apparent density of silica gels fired at different temperatures. The porosities were 58%, 46%, 44% and 33% for 200°, 400°, 600° and 800° C, respectively.

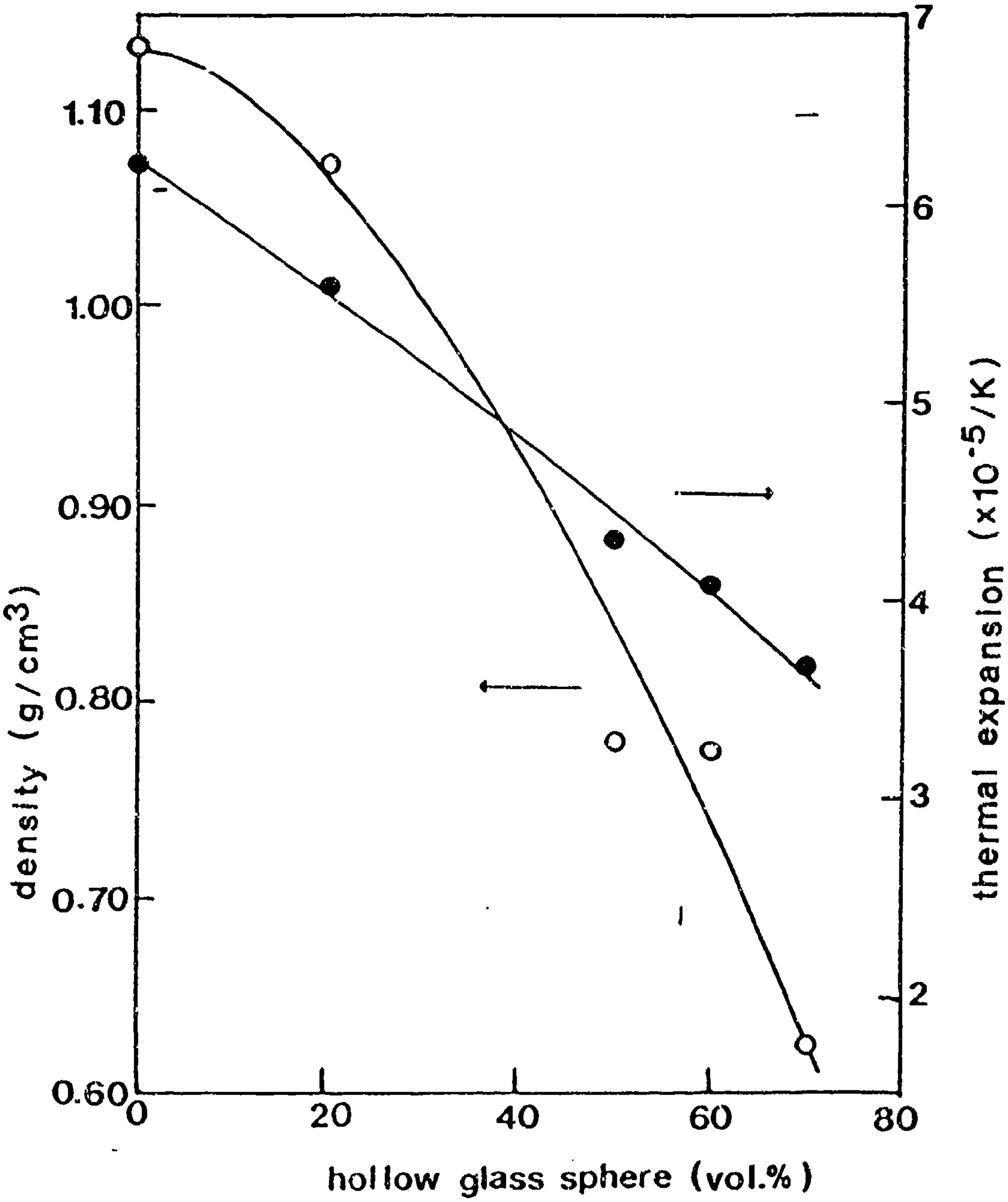

FIGURE 3: Expansion and density of resin-glass sphere composites.

composite samples whose thermal expansion coefficients were determined, some polymer-SiC-silica gel "triphasic" composites and hollow glass fiber-resin composites were studied. The general technique for the preparation of "triphasic" composites is shown in Figure 4. Measurements were made only at room temperature. Results are shown in Tables 4 and 5.

Some significant points to note are:

a. Because of the very thin-walled glass microballoons used, the glass contents of the samples in Table 4A were very minimal. This resulted in very low elastic moduli values for the composites as seen in Figures 5 and 6. Similar results were obtained by Lee and Westmann[21] who also developed equations for the approximate estimation of the elastic properties of such composites.

b. The silica gels studied were porous solids. The samples fired at 200°, 400°, 600° and 800°C had porosities of 58%, 46%, 44% and 33% respectively. With the exception of the 200°C sample, the results appeared to obey the relation.

$$E = E_o(1-1.9P + 0.9P^2) \quad (1)$$

Where E_o is the elastic modulus of silica glass.[22] Results are shown in Figures 7 and 8.

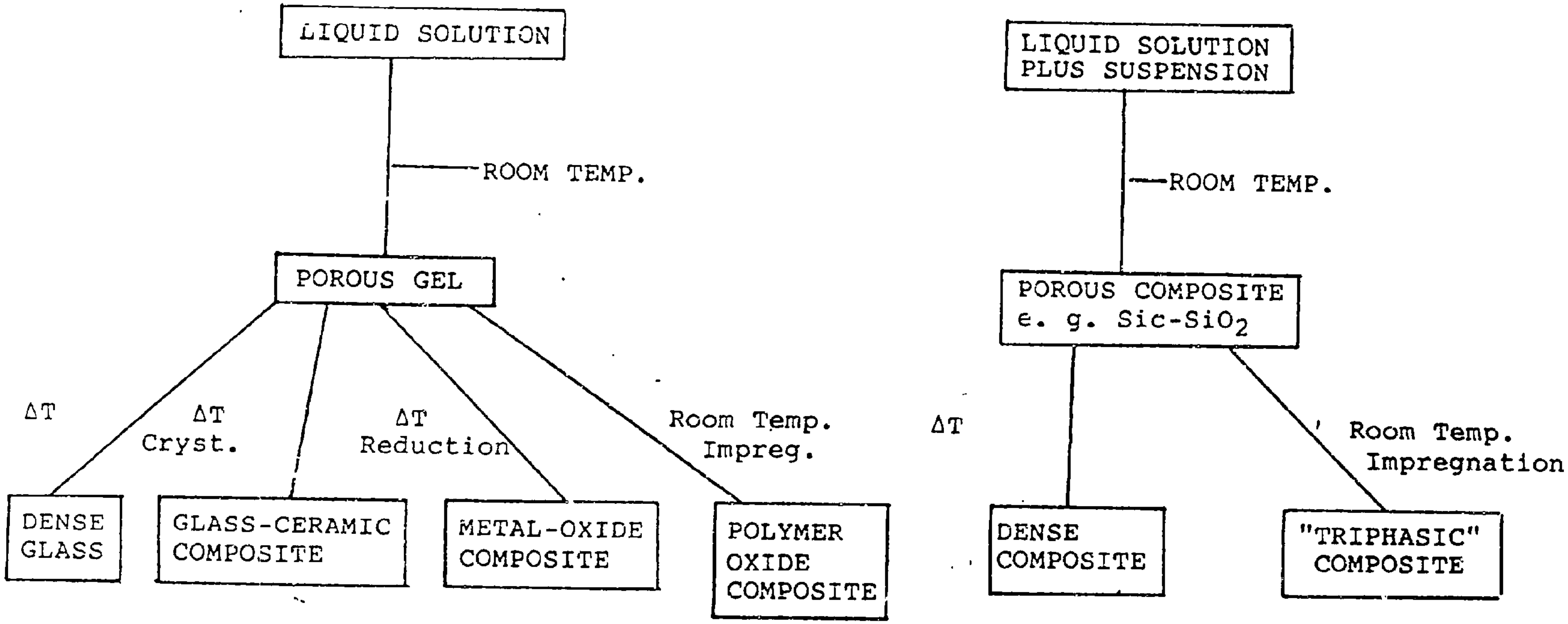

FIGURE 4: Sol-Gel Route to Porous and Dense Composites.

TABLE 4: Elastic moduli and density results at room temperature.

Glass balloons (vol.%)	Density (g/cm^3)	Young's modulus ($x10^5$ psi)	Shear modulus ($x10^5$ psi)	Bulk modulus ($x10^5$ psi)	Poissons's ratio
A. Glass balloons + Resin					
0	1.134	6.10	2.26	6.87	0.35
20	1.076	1h5.61	2.08	6.15	0.35
50	0.787	4.37	1.63	4.45	0.35
60	0.771	4.02	1.47	4.27	0.35
70	0.624	3.03	1.10	3.36	0.36
B. Conventionally melted and quenched glasses					
SiO_2	2.21	106	45	54	0.17
Pyrex	2.23	95	39	58	0 23
$Li_2O-Al_2O_3-SiO_2$ glass ceramics (pyroceram 9608)	2.60	124	50	83	0.25
$CuO-Al_2O_3-SiO_2$	2.73	98	43	60	0.23
High purity Al_2O_3 (polycrystalline)	3.6	392	148	363	0.32
PMMA + porous glass	1.83	25.6	10.3	16.4	0.24
PMMA + SiO_2-SiC Composite					
(600°C)	1.56	15.7	6.16	11.8	0.28
(1100°C)	1.98	52.2	21.4	30.7	0.22
Resin + hollow fiber	1.33			(I) 0.3 – 0.5	
		(II) impossible to measure sound velocity on account of high damping			
Resin + aluminum filled fiber	1.74	(II) impossible to measure sound velocity on account of high damping			

TABLE 5: Elastic moduli and density of silica gels and SiO_2-SiC composites.

SiO_2 gels

Heat-Treatment Temperature (°C)	Density (g/cm^3)	Young's Modulus ($x10^5$ psi)	Shear Modulus ($x10^5$ psi)	Bulk Modulus ($x10^5$ psi)	Poisson's ratio
200	0.93	8.74	3.27	7.28	0.30
400	1.20	20.4	7.98	15.5	0.28
600	1.24	28.4	11.7	16.5	0.21
800	1.49	48.1	20.2	26.1	0.19

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SiO_2-SiC composites

Heat-Treatment Temperature (°C)	Density (g/cm^3)	Young's Modulus ($x10^5$ psi)	Shear Modulus ($x10^5$ psi)	Bulk Modulus ($x10^5$ psi)	Poisson's ratio
20	2.19	4.6	1.84	2.92	0.24
600	2.40	10.8	4.37	6.75	0.23
800	2.40	13.7	5.62	8.31	0.22
1100	2.40	39.5	18.0	24.0	0.20

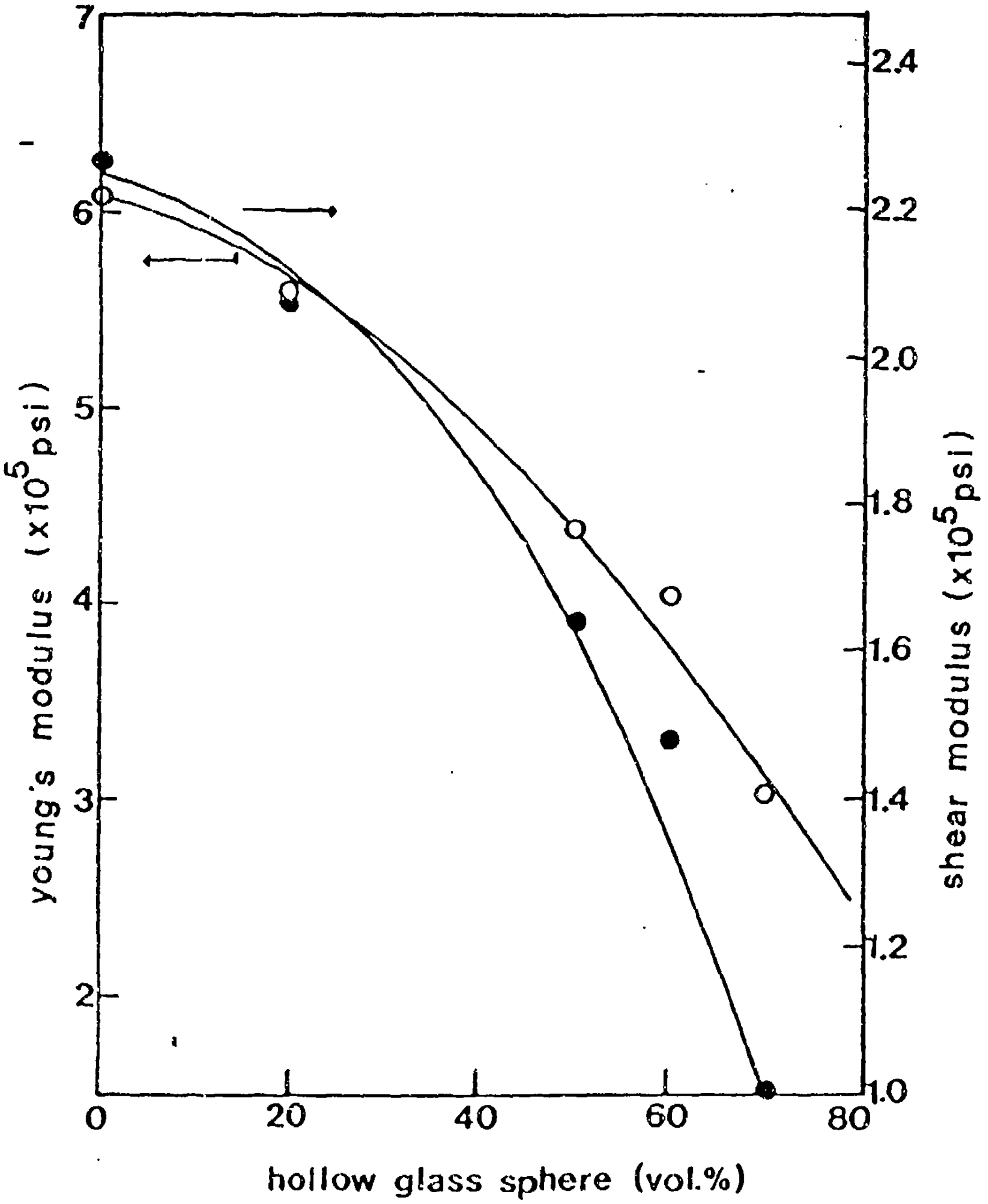


FIGURE 5: Young's modulus and shear modulus of resin-glass balloon composite.

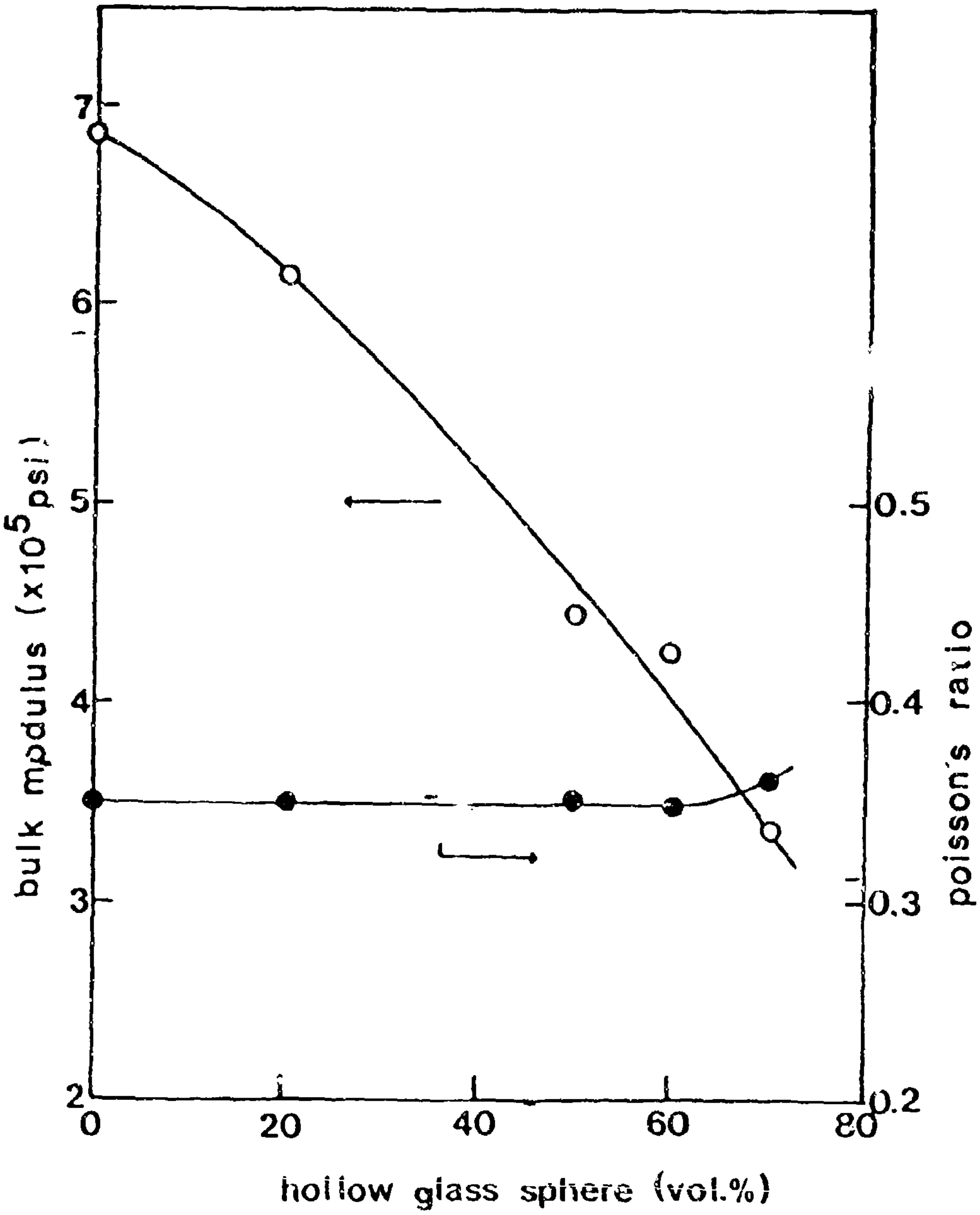


FIGURE 6: Bulk modulus and Poisson's ratio for resin-glass balloon composites.

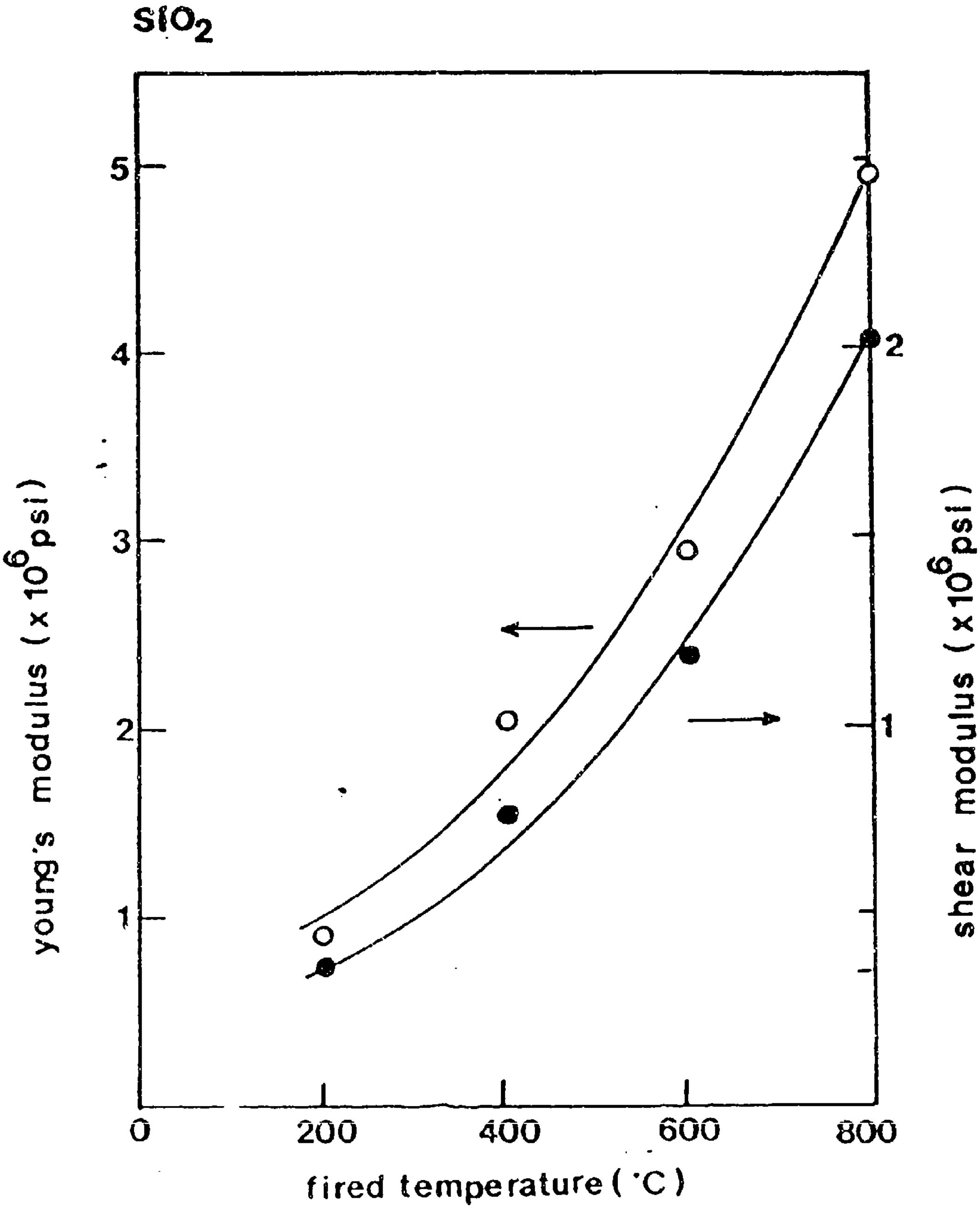


FIGURE 7: Young's modulus and shear modulus of silica gel as functions of firing temperature

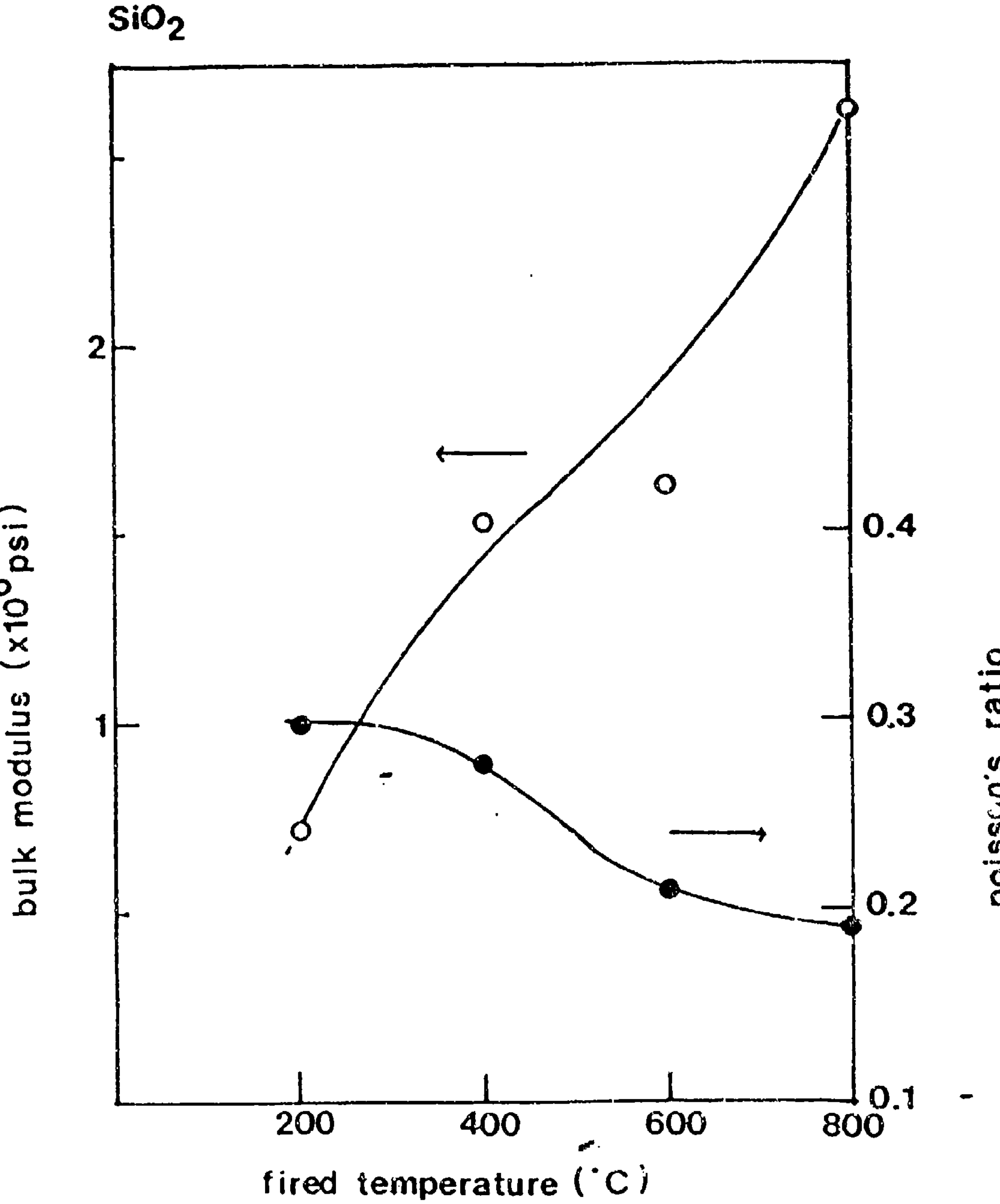


FIGURE 8: Bulk modulus and Poisson's ratio for silica gels fired at different temperatures.

D. Measurement of Damping Constants

Vibrational damping was studied for some of our composites with a low frequency resonance method.[23] An apparatus was designed and constructed and shown in Figure 9. Details of the samples configuration are shown in Figure 10. Results are shown in Table 6. The basic equation for calculating the relative damping constant b/c is:[24]

$$b/c = F_m/Af_o \tag{2}$$

Where F_m is the driving force at resonance, f_o is the resonant frequency of the sample and A is the amplitude of response signal at resonance. The damping coefficient of the materials is b and c is a system coupling constant. This technique was selected because of its relative simplicity and its demonstrated successful application.[23] The last column in Table 6 shows the results of $b/c\rho$ where ρ is the density in gm/cc. Based on damping above the composite made up of resin and 50% glass microballoons seems to be the best candidate.

IV. POTENTIALS OF NEW MATERIALS

A. Comparison with Other Materials

From published literature, graphite fiber/epoxy composites appeared to be the most promising candidate material for spacecraft structures (see Table 2 of Ref. 1). This is because of the high specific modulus and good damping behavior. The damping behavior in Table 1 of the report by Trudell, Curley and Rogers[1] is expressed as a "Loss Factor" whereas our results are obtained

FIGURE 9: LOW INTENSITY VIBRATIONAL DAMPING MEASUREMENT SYSTEM

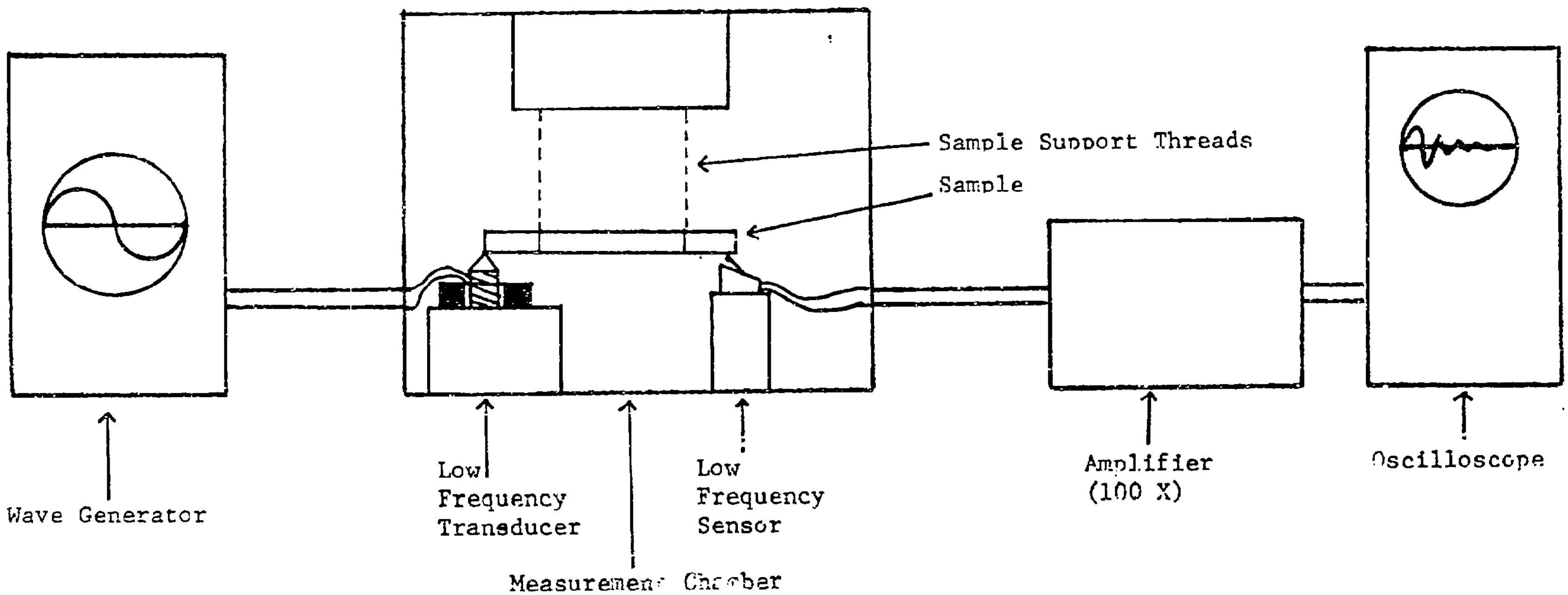
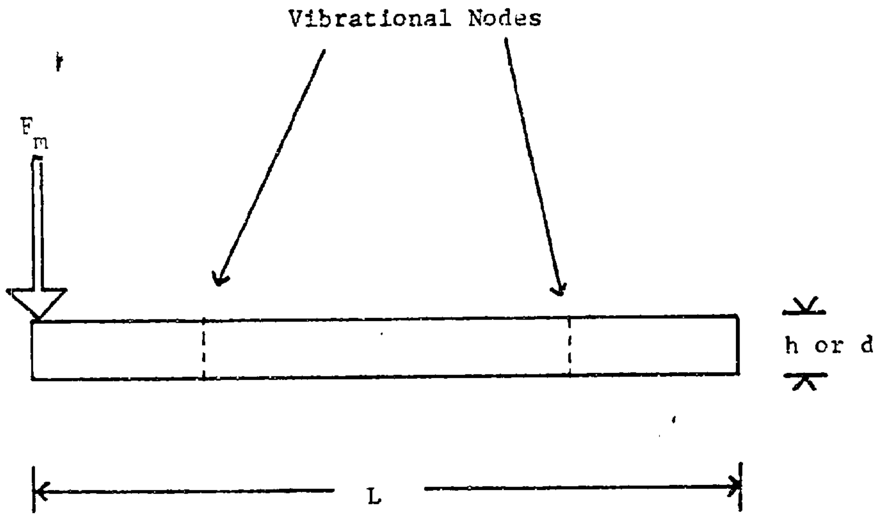


FIGURE 10

Important Sample Parameters for Vibrational

Damping Measurement by Resonance Method



L= length of sample

h or d = height or diameter of sample

F_m = driving force

Vibrational Nodes = 0.240 L and 0.760 L

TABLE 6: Relative damping constants and relative specific damping constants for selected materials based upon the resonance method.

Material	Resonant Frequency	Relative Damping Constant	Relative Specific Damping Constant
Inconel X-750	110 Hz	1.64	0.2
Alumina	120 Hz	1.50	0.38
Silica Glass	100 Hz	1.13	0.50
PMMA	28 Hz	4.10	3.40
Resin	29 Hz	12.10	10.70
* Resin/50% micro-balloons (glass)	33 Hz	12.10	15.40
* Resin/50% hollow glass fibers (11)	46 Hz	6.50	4.90
* Resin/50% glass-aluminum fibers (11)	76 Hz	3.80	2.10

* Material developed at UCLA

in the form of damping constants. An approximate conversion however has now been made to permit the comparison of the current material and the graphite-epoxy composites. The relevant results are shown in Table 7 and Fig. 11. From Table 7, it would appear that of those materials on which experimental measurements have been made, graphite-epoxy composites have the highest specific modulus and relatively good damping behavior.

Although the present project was very limited in time and resources it does reveal some promising future generation of composites which could perhaps be superior to the graphite-epoxy materials currently known. For example, an "ideal" candidate could be a composite made up of hollow ceramic fibers embedded in a sol-gel derived matrix of similar expansion coefficient. The sol-gel matrix, because of its interconnecting pores, could further be filled with an organic resin to obtain improved damping. Such a proposed structure is shown in Figure 12. If the ceramic hollow fiber has low expansion coefficient and is similar to that of the sol-gel derived matrix, then the expansion coefficient of the entire composite should also be small irrespective of direction. The amount of resin used is significantly smaller than that used in the graphite/epoxy composite. Also because of the ultrafine pore of the sol-gel derived matrix, the resin is protected from the hostile environment. The electrical resistivity of the new composite should also be very high.

TABLE 7: Comparison of specific modulus and damping of various materials.

Material	Specific Modulus (x 10^6 in)	Relative DampingPCalculated Constant (b/c)	Specific Loss Factor	Relative Damping Constant
Inconel	136	1.64	0.0004	0.2
Alumina	301	1.50	0.0004	0.38
Silica Glass	125	1.13	0.0003	0.50
PMMA	10	4.10	0.0032	3.40
Resin	9	12.10	0.0260	10.70
Resin/ Micro-balloon	16	12.10	0.0260	15.40
Resin/ Hollow Fibers		6.50	0.0080	4.90
Resin/ Alum-Glass Fibers	80	3.80	0.0030	2.10
Epoxy-Graphite Composites		Calculated Relative Damping Constant	Measured Loss Factor	Calculated Relative Specific Damping Constant*
Type I (//)	407	5.5	0.0060	3.90
Type II (//)	466	5.8	0.0070	4.14
Type II (/)	19	8.8	0.0140	6.30

* Density for graphite-epoxy composite assumed to be 1.40 gm/cc.

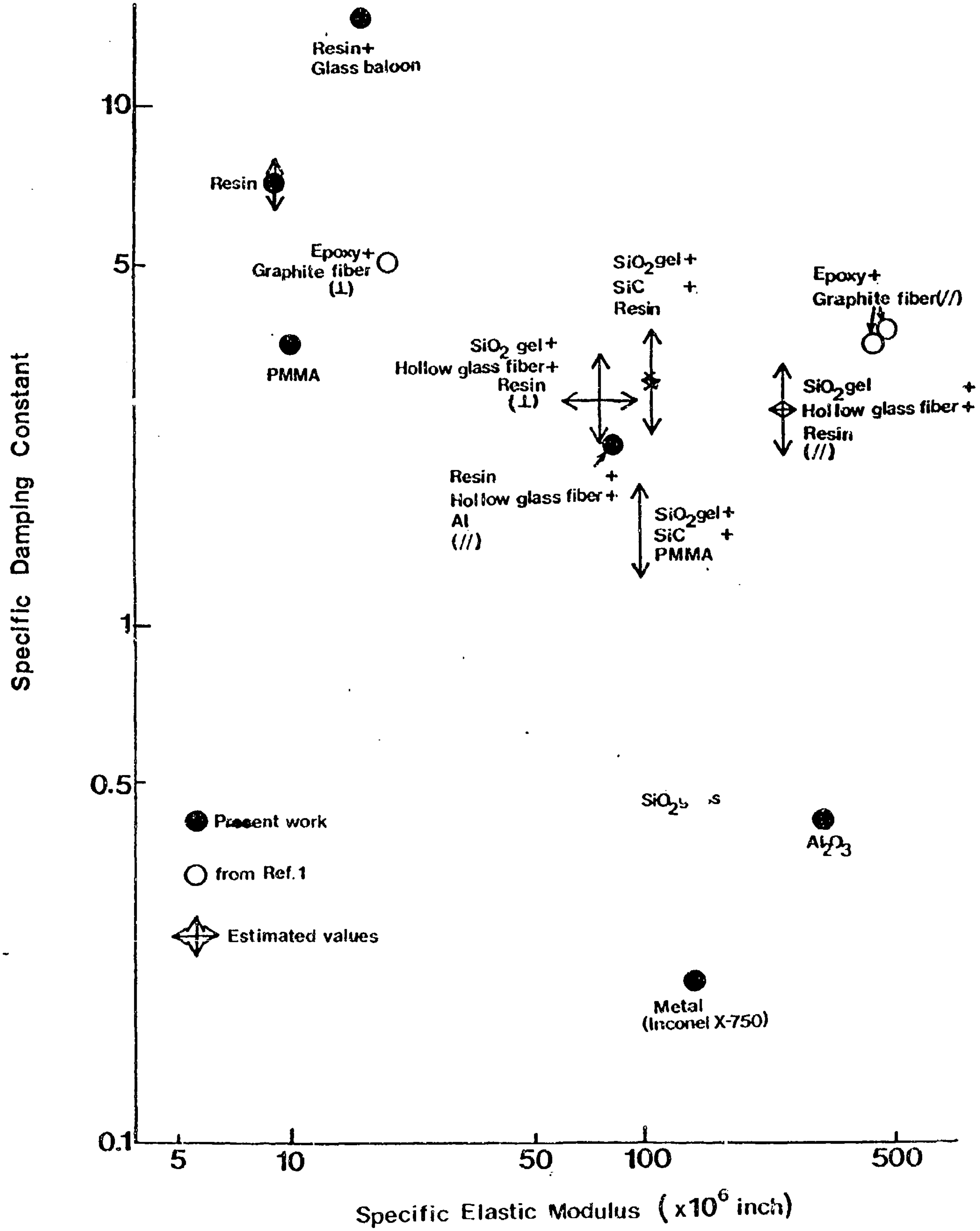


FIGURE 11: Damping-modulus relationship for various materials

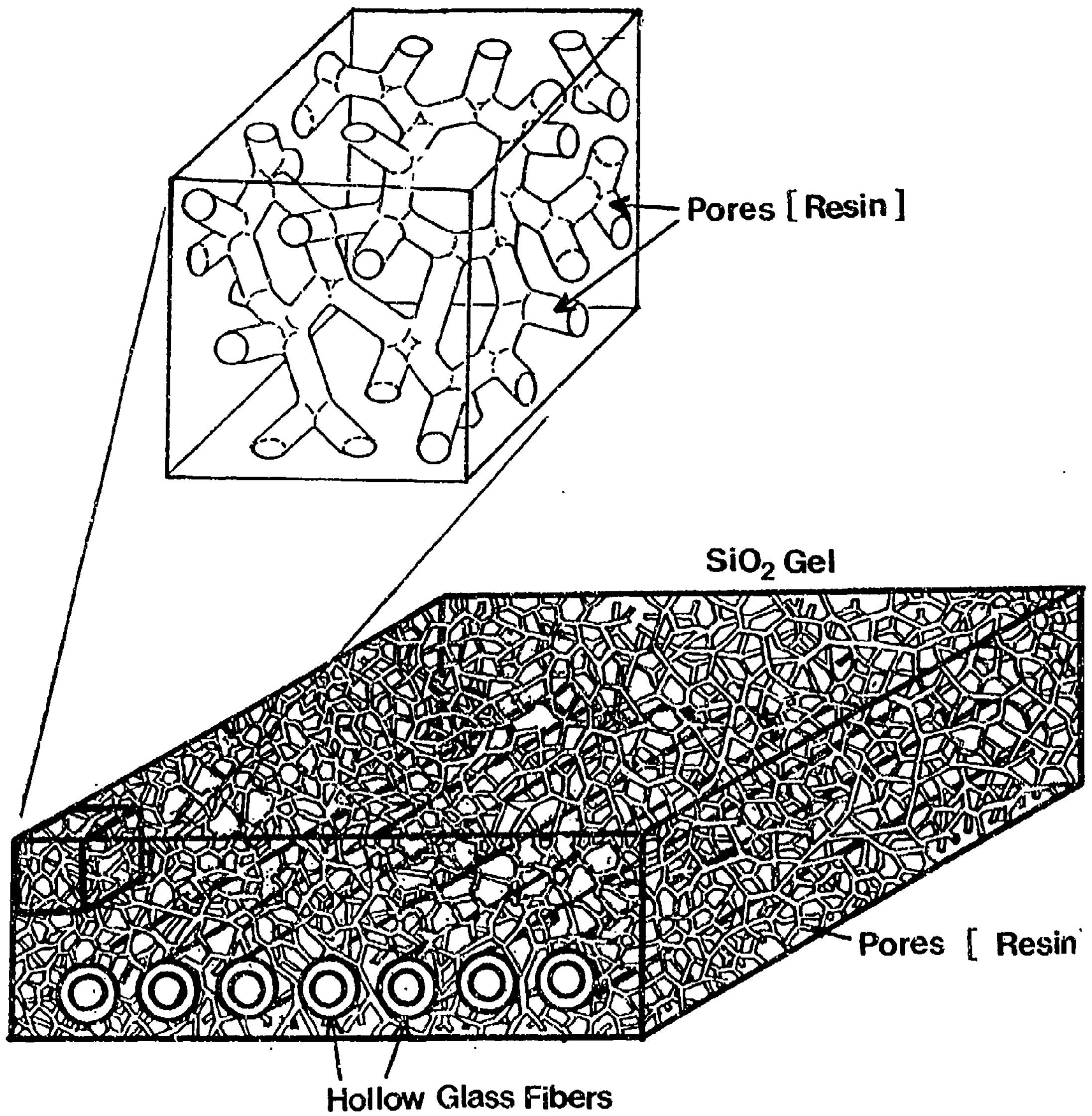


FIGURE 12: A proposed composite material for spacecraft applications.

B. Recommendations for Future Work

This brief feasibility study has revealed that some new composites based on hollow glass or ceramic fibers of low expansion embedded in a sol-gel derived matrix also with a low expansion coefficient can lead to materials of potential usefulness for spacecraft structures provided the sol-gel matrix is further impregnated with an organic resin to promote damping. Glass microballoons can also be used in place of the hollow glass fibers. Hollow glass fibers can be prepared from silica or from copper aluminosilicate glasses both of which have low expansion coefficients from -200° to +200°C. Hollow fibers based on low expansion lithium aluminosilicate glass-ceramics should also be applicable. Hollow fiber geometry could further be exploited in the form of aligned oval fibers when the stiffness can be increased four times for the same weight. The hollow fibers themselves can also be filled with other materials to further control the property of the composite.

It is evident from the above considerations that further research and development on these new composites based on a sol-gel derived matrix is highly recommended.

V. PERSONNEL

Dr. H. Nasu, Mr. Edward Pope and Ms. Alana Nakata contributed significantly to this project.

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APPENDIX 1

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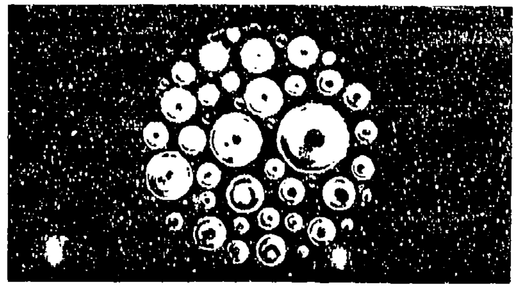
APPENDIX 2

EMMERSON AND CUMING, INC. Dielectric Materials Division

Technical Bulletin 14-2-2 ECCOSPHERES SI Hollow Silica Microspheres

EMERSON & CUMING, Inc.
Dielectric Materials Division
Plastics/Ceramics for Electronics

TECHNICAL BULLETIN 14-2-2
ECCOSPHERES® SI
Hollow Silica Microspheres



ECCOSPHERES SI are micron sized, thin walled bubbles made from silica. They are supplied as a fine, free flowing powder. Particle size is in the range 30 to 180 microns; wall thickness is about 1.5 microns. Bulk density is about 11 lbs/cu. ft. (0.176 g/cc). The material is stable at temperatures to 1700°F (925°C). Electrical properties are excellent.

ECCOSPHERES SI are used in a variety of applications. They can be incorporated in plastics to produce light weight materials. For example, ECCOSPHERES SI in polyethylene has resulted in a product density of less than 40 lbs/cu. ft. (0.64 g/cc) with a dielectric constant below 1.7. Low electrical loss has been preserved, as have the desirable physical characteristics of polyethylene. ECCOSPHERES SI can be bonded to themselves to produce foamed silica sheet stock. Conventional ceramics have incorporated these particles. ECCOSPHERES SI have even been incorporated in molten metals to produce light weight castings. Loose ECCOSPHERES SI can be used for thermal insulation and space filling.

ECCOSPHERES SI alone or in combination with other materials should have numerous applications in space technology and electronics. Light weight, high temperature capability, excellent ablation characteristics and low dielectric constant are a few of the features of this product.

Typical Properties:

Physical Form		Free Flowing Powder
True Particle Density (Liquid Displacement) gm/cc (lb/ft^3)		0.254 (15.8)
Bulk Density (Tamped) gm/cc (lb/ft^3)		0.152 (9.5)
Packing Factor		0.559
Particle Size Range, Microns (% by weight)	175 (0)	100-125 (12)
	149-175 (14)	62-100 (40)
	125-149 (10)	44- 62 (15)
		44 (9)
Average Particle Diameter, Microns (weight basis)		80
Average Wall Thickness, Microns (weight basis)		1.5
Thermal Conductivity of Loosely Packed Material (BTU)(in)/(hr)(ft^2)(°F)-(cal)(cm)/(sec)(cm^2)(°C)	at 0°F	.36 (0.00012)
" "	at 300°F	.50 (0.00017)
Softening Temperature, °F (°C)		1800 (980)
Dielectric Constant (dry) 1 MHz to 8.6 GHz		1.2
Dissipation Factor (dry) 1 MHz to 8.6 GHz		0.0005

Tight goggles (no ventilation holes) and a dust mask should be worn when handling. If Microballoons® are deposited in the eye, severe irritation may result, requiring the attention of a physician. Although breathing in Microballoons poses no known serious problems, such as Silicosis, (Gross et. al. AMA Archives of Industrial Health 21:10, 1960), it does constitute at least a nuisance and should be avoided.

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